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A MAGNETIC FIELD MEASUREMENT TECHNIQUE USING A MINIATURE TRANSDUCER

by Carl L. Fales, Jr., Roger A. Breckenridge,
and William J. Debnam, Jr.

Langley Research Center
Hampton, Va. 23665

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16. Abstract

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SUMMARY

This study describes the development, fabrication, and application of a magnetometer. The magnetometer has a miniature transducer and is capable of automatic scanning. The magnetometer described here is capable of detecting static magnetic fields as low as 1.6 A/m and its transducer has an active area 0.64 mm by 0.76 mm. Thin and rugged, the transducer uses wire, 0.05 mm in diameter, which is plated with a magnetic film, enabling measurement of transverse magnetic fields as close as 0.08 mm from a surface. The magnetometer, which is simple to operate and has a fast response, uses an inexpensive clip-on milliammeter (commonly found in most laboratories) for driving and processing the electrical signals and readout. A specially designed transducer holding mechanism replaces the XY recorder ink pen; this mechanism provides the basis for an automatic scanning technique. The instrument has been applied to the measurements of magnetic fields arising from remanent magnetization in experimental plated-wire memory planes and regions of magnetic activity in geological rock specimens.

INTRODUCTION

This study describes a magnetometer which has a miniature transducer and is capable of automatic scanning. The magnetometer was developed to provide an external means of determining the presence of magnetic remanence in the magnetic word-strap keepers on memory planes of experimental plated-wire memories. (See refs. 1 and 2.) If regions of magnetic remanence exist in the keepers, the operation of the memory can be affected by a change in the orientation of the magnetization of the plated wire. Dynamic measurements at each bit location of prototype memory planes prior to assembly of the entire memory system are extremely time consuming. Therefore, an external means of determining the presence of magnetic remanence in the memory planes was highly desirable.

Magnetic sensors existed that would measure these transverse fields very close to the surface of the word-strap keeper. However, their size was typically on the order of 0.25 cm by 0.75 cm, so that magnetic hot spots or remanent magnetization could not be resolved accurately.

The magnetometer is based on the time variation of the magnetic permeability in the magnetic material of the transducer (see ref. 3), but its operation is substantially different from the ordinary flux-gate magnetometer. The underlying principle of operation of the transducer is similar to that described in references 4 and 5 by S. Oshima and others. The transducer described by these authors uses plated wire 0.20 mm in diameter and has a size in one dimension of approximately 1.0 cm. Furthermore, it requires the use of special electronic instrumentation.

The unique feature of the magnetometer described in this paper is that its transducer has an active region of approximately 0.64 mm by 0.76 mm and is therefore capable of very good spatial resolution of magnetic fields of as low as 1.6 A/m. The magnetometer has other attractive features. It is simple to operate, has a fast response, and employs an automatic transducer scanning technique. In addition, it has a rugged and flat transducer and can measure magnetic fields as close as 0.08 to 0.10 mm from any relatively flat surface.* Another application of the magnetometer, also covered in this study, involves the measurement of transverse magnetic field components at the surface of geological rock specimens.

SYMBOLS

A_o	total cross-sectional area of the magnetic wire coatings, cm^2
B_r	radial (r) component of magnetic flux density, T
B_z	axial (z) component of magnetic flux density, T
B_ϕ	circumferential (ϕ) component of magnetic flux density, T
H_o	axial (z) component of external magnetic field intensity, A/m
H_r	radial (r) component of magnetic field intensity, A/m
H_z	axial (z) component of magnetic field intensity, A/m
H_ϕ	circumferential (ϕ) component of magnetic field intensity, A/m
N	number of turns in sense coil

*Helpful suggestions on the design of the transducer and the utilization of a clip-on milliammeter were given by A. V. Pohm of Iowa State University.

r	radial distance from center of plated wire, cm
$\hat{r}$	radial unit vector
V_s	open-circuit voltage across sense coil, V
z	distance along axial direction of plated wire, cm
$\hat{z}$	axial unit vector
μ_{zz}	magnetic permeability associated with z-direction, $\left(\frac{\partial B_z}{\partial H_z}\right)_{H_z=0}$, $\frac{T}{A/m}$
$\frac{d\mu_{zz}}{dt}$	time derivative of magnetic permeability associated with z-direction, $\frac{T}{A\text{-}sec/m}$
ϕ	polar angle in circumferential direction around plated wire, rad
$\hat{\phi}$	polar angle unit vector

THEORY

Figure 1 is a schematic diagram of the magnetic transducer. The drive circuit is constructed of four wires plated with magnetic material which are connected in series by copper wire. The plated wire consists of a thin layer of nickel-iron magnetic alloy plated on a copper-beryllium substrate. The drive circuit has 10 to 30 turns of copper wire wound around it which serve as a sense coil.

The plated wire is magnetically anisotropic with the easy direction circumferentially to the wire and with the hard direction along the wire axis. There is negligible hysteresis in the hard direction, relative to the easy direction. The approximate values for the saturation magnetic field intensity in the hard direction and the easy direction breakpoint are 320 A/m and 160 A/m, respectively.

The following description of the concept of the transducer operation is both brief and qualitative. A more detailed discussion is presented in the appendix. The transducer is driven sinusoidally at a frequency of 20-kHz and 125-mA peak. The current is sufficient to drive the magnetic coating of the wire into saturation in the circumferential direction twice each cycle. As a result, the magnetic permeability associated with the axial direction of the wire is reduced twice each cycle to a small value coincident with the alinement of the magnetic domains in the circumferential direction. For sufficiently small external axial magnetic field intensities, the axial magnetic flux density is the product of the external field and the magnetic permeability. Since the sense coil links predominately the axial magnetic flux, then, by Faraday's law, the open-circuit voltage developed across the sense coil has a dominant 40-kHz component and is proportional to the magnetic field perpendicular to the plane of the same coil and along the length of the magnetic wires.

TRANSDUCER FABRICATION

The basic elements of the magnetic field transducer are four plated magnetic wires. The wire consists of approximately 0.5 to 1.0 μm of a nickel-iron alloy plated on a 0.05-mm-diameter beryllium-copper substrate. Initially, the plated wires are cut approximately 1.90 mm long for purposes of handling. Then the wires are masked with either photoresist or thinned coil dope and are etched in ferric chloride so that a 0.56-mm to 0.64-mm length of magnetic film is left on the wire. The wires are now rinsed with distilled water and alcohol and allowed to dry. The masking material is then removed, and the wires are again rinsed in alcohol and dried.

Next, the four etched wires are mounted in a removable form to insure that they are parallel on 0.25-mm centers. For smaller spacings, care should perhaps be taken to insure that undesirable magnetic interactions and cancellations of the driving field do not occur in parts of the film. Depending on the desired sensitivity and sensor to magnetic sample separation distance, 10 to 30 turns of 0.025-mm-diameter insulated copper wire are then wound around the plated portion of the etched wires to form a sense coil. The wire assembly is now coated with a clear epoxy, which is then cured at 60° C for 2 hours. The wire assembly is carefully removed from the form, and electrical leads are attached between the etched portions of the four plated wires as close to the magnetic film as possible.

The connections are made so that the plated wires are in series and constitute the drive circuit. Two methods are used here to attach the electrical leads: one is to bond the gold wire by thermocompression and the other is to solder the copper wire. The excess portion of the etched wire is then trimmed off as close to the electrical connections as possible.

The transducer is now completed (see fig. 2) and is ready for mounting. At this point, electrical continuity of the drive circuit and the sense coil are checked by measurement of their respective resistances. The transducer is then mounted in a hole in a printed circuit board with transparent epoxy so that it can be as near as possible to the material on which the magnetic measurements are to be performed and still be protected from physical damage. (See fig. 3.) Registration marks on the printed circuit board allow for proper alinement of the transducer with respect to the region to be tested.

MAGNETOMETER CHARACTERISTICS AND SCANNING APPARATUS

Several conventional laboratory instruments, including a clip-on milliammeter and two XY recorders, are employed in the magnetometer. A Hewlett-Packard model 428B clip-on milliammeter delivers the 20-kHz drive signal, which is stepped up by a transformer to the required current level. The transformer and transducer replace the 428B milliammeter current probe.

The clip-on milliammeter performs the following electrical functions. The 40-kHz sense signal is returned to the milliammeter where it undergoes synchronous detection and amplification. A fraction of the output current is returned as a direct current negative feedback to the sense coil, which, in turn, generates a direct current magnetic field that very nearly cancels the external field to be measured. The output signal of the synchronous detector becomes almost zero, and the feedback current monitored by the meter is proportional to the external magnetic field.

The transducer was calibrated by a strip conductor carrying a known current, by a loop carrying a known current, and also by direct comparison with a precision Hall probe gaussmeter. All three methods agree within 10 percent. For routine calibration experiments, the strip conductor is used. A plot of milliammeter reading as a function of the external magnetic field was obtained experimentally and is shown in figure 4. The calibration is linear from approximately 1.6 A/m to 180 A/m, with a meter sensitivity of $0.033 \frac{\text{mA}}{\text{A/m}}$. A 20-percent deviation from linearity exists at 360 A/m, beyond which saturation effects dominate. This magnetic field value is in qualitative agreement with the saturation value of roughly 320 A/m previously discussed.

Figure 5 is a plot of the clip-on milliammeter sensitivity as a function of the peak drive current in the plated wires for an external field of 80 A/m; the same results were obtained for a field of 40 A/m. The sensitivity increases rapidly for currents below 125 mA and finally levels out in the range of 300 mA. The operating point of 125 mA gives sufficient sensitivity for the applications discussed in this study and limits power dissipation in the drive circuit of the transducer. There is no perceptible meter deflection below a drive current of 28 mA. This current corresponds to a magnetic field intensity of 180 A/m in the magnetic coating of the circumference of the wire. It was noted previously that an approximate value of the easy direction breakpoint is 160 A/m. In general, it is desirable to keep the amount of magnetic material in the transducer to a minimum in order to reduce the perturbation of the magnetic fields of the sample on which measurements are to be made. If more magnetic material in the transducer does not pose a problem, then, for a given transducer size, the sensitivity can be increased by using wires with thicker magnetic coatings and by placing the plated magnetic wires closer together.

A novel scanning apparatus using two commercially available XY recorders was developed to assist in the measurement of the transverse magnetic field on relatively flat surfaces. Although the arrangement does not provide for precision scanning, it can be readily assembled and permits relatively rapid measurements to be made. Figure 6 is a photograph of the experimental arrangement. Figure 7 shows a picture of the transducer holding mechanism that replaces the recorder ink pen. A signal proportional to the transducer output is fed to another XY recorder whose sweep is synchronized to the scanning recorder. After the desired scan line oriented along the x-direction is marked (for example, by colored ink), the transducer is placed above the line of interest with the y-position control, and a slow time sweep in the x-direction is initiated. The transducer and the object whose magnetic field is to be measured are placed inside a Mumetal box located on the XY recorder. The box shields against the Earth's magnetic field and magnetic fields originating from the XY recorder.

APPLICATIONS

Plated-Wire Memory

Figure 8 presents a sketch of the cross section of a plated-wire memory with plated magnetic word-strap keepers and the position of the magnetic transducer relative to a keeper. The memory consists of a cross grid of plated memory wires and copper word straps. The cross-hatched region surrounding a word strap is a nickel-iron alloy magnetic keeper. The purpose of the plated keeper is to enhance the operation of the plated wire as a memory element. If regions of remanent magnetization exist in the keepers, the orientation of the magnetization of the plated wire will change as a function of both time and temperature, and thereby degrade the operation of the plated wire. Magnetic anomalies in the word-strap keepers give rise to a magnetic field which can be measured by the magnetometer as the transducer is moved along a single word strap.

The transducer has an active region capable of resolving spatially an area defined by one word strap and four crossovers with the plated memory wire. It responds only to the magnetic field which is transverse to the word strap (the magnetic field component that adversely affects the memory wire). As the transducer is located the same distance from the top of the keeper as the memory wire, it is felt that this is a reasonable external measurement method for obtaining an estimate of the magnetic field magnitude at the memory wire. Since the zero control on the milliammeter can be used to compensate for the Earth's magnetic field, the Mumetal box is not needed for this measurement. Furthermore, the variations in the induced fields due to the XY recorder are small relative to the remanent magnetization fields in the word-strap keepers. Through the use of an external vacuum pump, the paper vacuum holddown mechanism of the XY recorder is used to pull the memory plane flat after the edges of the memory plane are taped down to insure a relatively good vacuum. This procedure establishes a stress reference condition and eliminates ripples in the memory plane.

Figure 9 shows a typical readout obtained from the magnetometer which is scanned by the apparatus previously described. The magnetic field transverse to the word strap is plotted for three adjacent straps as a function of the distance along the word strap on an experimental memory plane. The fields vary drastically from one word strap to an adjacent one. Therefore, the one-strap resolution of the transducer is a useful diagnostic tool in studies of the nature of the magnetic anomalies (for example, magnetostriction) in plated-wire memory planes.

Geological Applications

Another application of the magnetometer is the measurement of both transverse components of the magnetic field taken 0.15 mm above the surface of several geological rock samples. The rock sample is placed inside a Mumetal box which serves as a magnetic shield from both the Earth's field and that of the XY recorder. The shielding is more critical here than for the memory plane since fields of as low as 0.8 A/m to 1.6 A/m are being measured.

The first orientation of the transducer gives a field measurement in a direction normal to the sweep line. The sweep lines are drawn in colored ink on the surface of each rock sample. Then the probe is rotated 90° counterclockwise to measure the magnetic field in a direction along the sweep line.

In figure 10 the transverse magnetic field is plotted as a function of distance along a rock sample known to contain hematite and ilmenite – materials that can be expected to exhibit magnetic activity. The upper trace shows the y-component (perpendicular to the sweep line) and the lower trace, the x-component (along the sweep line) of the magnetic fields, both taken on the same sweep line. Note the regions of magnetic activity and, in particular, the difference in information contained in the mutually perpendicular field components at several locations. Complete information on the surface magnetic field can be obtained by using a small Hall probe gaussmeter to measure the vertical field component.

CONCLUSIONS

A magnetometer with a miniature scanning transducer capable of automatic scanning was developed. The magnetometer described in this study has the following characteristics: (1) the transducer has an active region of approximately 0.64 mm by 0.76 mm and is capable of detecting static magnetic fields of as low as 1.6 A/m; (2) plated wire 0.05 mm in diameter, employed in the transducer, allows the measurement of transverse magnetic fields as close as 0.08 mm from surface; (3) the magnetometer uses an inexpensive clip-on milliammeter (commonly found in most laboratories) for driving and processing the electrical signals and readout; and (4) a specially designed transducer holding mechanism that replaces the XY recorder ink pen, and provides the basis for an automatic scanning technique. The capabilities of the magnetometer were successfully demonstrated in two different applications. The various parameters of the device, such as transducer size and sensitivity, can be tailored to suit particular applications.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., July 24, 1974.

APPENDIX

PRINCIPLES OF OPERATION OF MAGNETOMETER

Since this study describes the development, fabrication, and application of a magnetometer, a more detailed description of the principles of operation than given in the body of the paper is presented here. The discussion remains primarily qualitative.

Figure 11 is a drawing of the plated-wire coordinate system. The low-frequency relations between the vector magnetic flux densities (both inside and outside the wires) and the magnetic field intensities are given by

$$B_z = B_z\left(H_r, H_\phi, H_z\right) \tag{1}$$

$$B_\phi = B_\phi\left(H_r, H_\phi, H_z\right) \tag{2}$$

$$B_r = B_r\left(H_r, H_\phi, H_z\right) \tag{3}$$

where the functions are multivalued due to hysteresis, that is, they depend on the time history of the excitations. Radial fields have little effect since there is a strong shape anisotropy field constraining the film magnetization to lie in a direction tangential to the cylindrical surface of the wire. By neglecting radial fields, equations (1) to (3) reduce to

$$B_z = B_z\left(H_\phi, H_z\right) \tag{4}$$

$$B_\phi = B_\phi\left(H_\phi, H_z\right) \tag{5}$$

A special magnetic film property made use of here guarantees that the hysteresis associated with the hard direction is small. If H_z, the magnetic field in the z-direction, is small and a Taylor expansion about $H_z = 0$ is valid, then equations (4) and (5) become, respectively,

$$B_z = B_z\left(H_\phi, 0\right) + \left(\frac{\partial B_z}{\partial H_z}\right)_{H_z=0} H_z \tag{6}$$

$$B_\phi = B_\phi\left(H_\phi, 0\right) + \left(\frac{\partial B_\phi}{\partial H_z}\right)_{H_z=0} H_z \tag{7}$$

Ideally, $B_z\left(H_\phi, 0\right) = 0$. Also, since a major hysteresis loop exists in the ϕ-direction, since the z-axis is a hard direction of magnetization, and since H_z is assumed to be small, $B_\phi\left(H_\phi, 0\right) >> \left(\frac{\partial B_\phi}{\partial H_z}\right)_{H_z=0} H_z$. In the linear approximation, equations (6) and (7) are, respectively,

$$B_z = \mu_{zz}\left(H_\phi\right)H_z \tag{8}$$

$$B_\phi = B_\phi\left(H_\phi\right) \tag{9}$$

where $\mu_{zz}\left(H_\phi\right)$ is the magnetic permeability associated with the axial direction of the wire and is defined by

$$\mu_{zz}\left(H_\phi\right) = \left(\frac{\partial B_z}{\partial H_z}\right)_{H_z=0} \tag{10}$$

End effects and the demagnetizing field due to the magnetic wires are presumably small. Therefore, $H_z = H_o$ both inside and outside the magnetic wires, where H_o is the z-component of the static external magnetic field to be measured along the direction of the magnetic wires. It is assumed that the external field does not vary spatially over the active region of the transducer. The magnetic flux that links the sense coil is approximated by the z-component of flux perpendicular to the plane of the sense coil and along the length of the magnetic wires. Furthermore, since the z-component field outside the wires is constant in time, only the field in the magnetic film is important.

As a consequence of Faraday's law, the open-circuit voltage developed across the sense coil is (in units of volts)

$$V_s = \left(10^{-8}\right)NA_o \frac{d\mu_{zz}}{dt} H_o \tag{11}$$

where A_o is the total cross-sectional area of the magnetic wire coatings and N is the number of turns in the sense coil.

For purposes of illustration, a highly idealized symmetrical plot of the permeability associated with the axial (z) direction $\mu_{zz}\left(H_\phi\right)$ is shown in figure 12 as a function of the drive circuit field H_ϕ. By using the same H_ϕ-axis, the drive circuit field as a function of time is also given. The transducer (see fig. 1) is driven sinusoidally at a frequency of 20-kHz and 125-mA peak. The current is sufficient to drive the magnetic coating of the wire into saturation in the circumferential direction twice each cycle. (See eq. (9).) As a result, the magnetic permeability associated with the axial direction of the wire (eq. (10)) is reduced twice each cycle to a small value coincident with the alinement of the magnetic domains into the circumferential direction. This waveform is obtained by projecting (see the dashed line in fig. 12) from the drive field waveform $H_\phi(t)$ up to the plot of $\mu_{zz}\left(H_\phi\right)$ and then across to yield $\mu_{zz}(t)$ as a function of time. For sufficiently small, external, axial, magnetic field intensities, the axial magnetic flux density is the product of the external field and the magnetic permeability. (See eq. (8).)

Since the sense coil links predominately the axial magnetic flux, then as a consequence of Faraday's law (eq. (11)) the open-circuit voltage developed across the sense coil has a dominant 40-kHz component and is proportional to the magnetic field perpendicular to the plane of the same coil and along the length of the magnetic wires. The time derivative of $\mu_{ZZ}(t)$ is drawn (see fig. 12) below the waveform of $\mu_{ZZ}(t)$ and clearly demonstrates two complete cycles occurring in the drive field fundamental period of $T = 50$ μsec.

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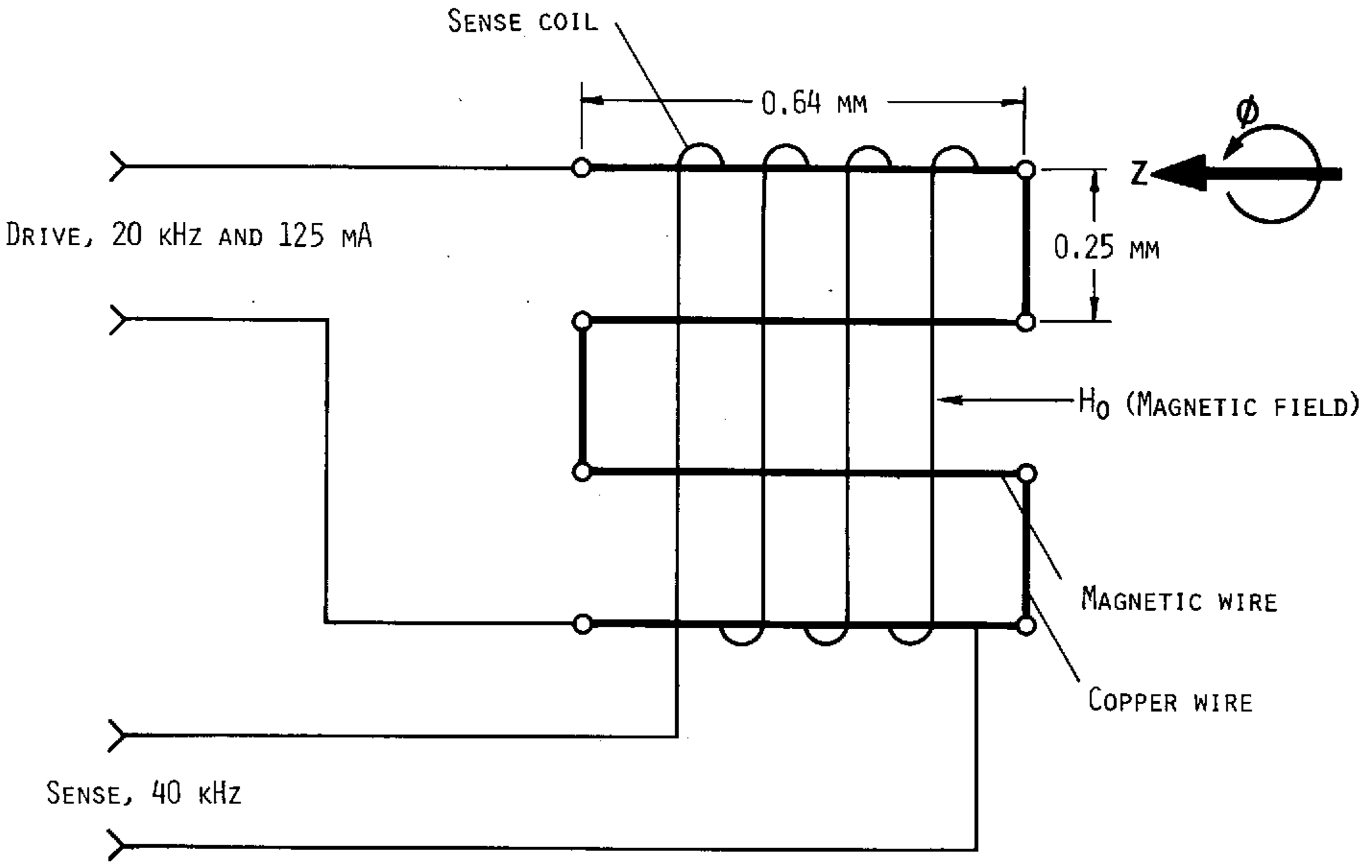

Figure 1.- Schematic diagram of transducer.

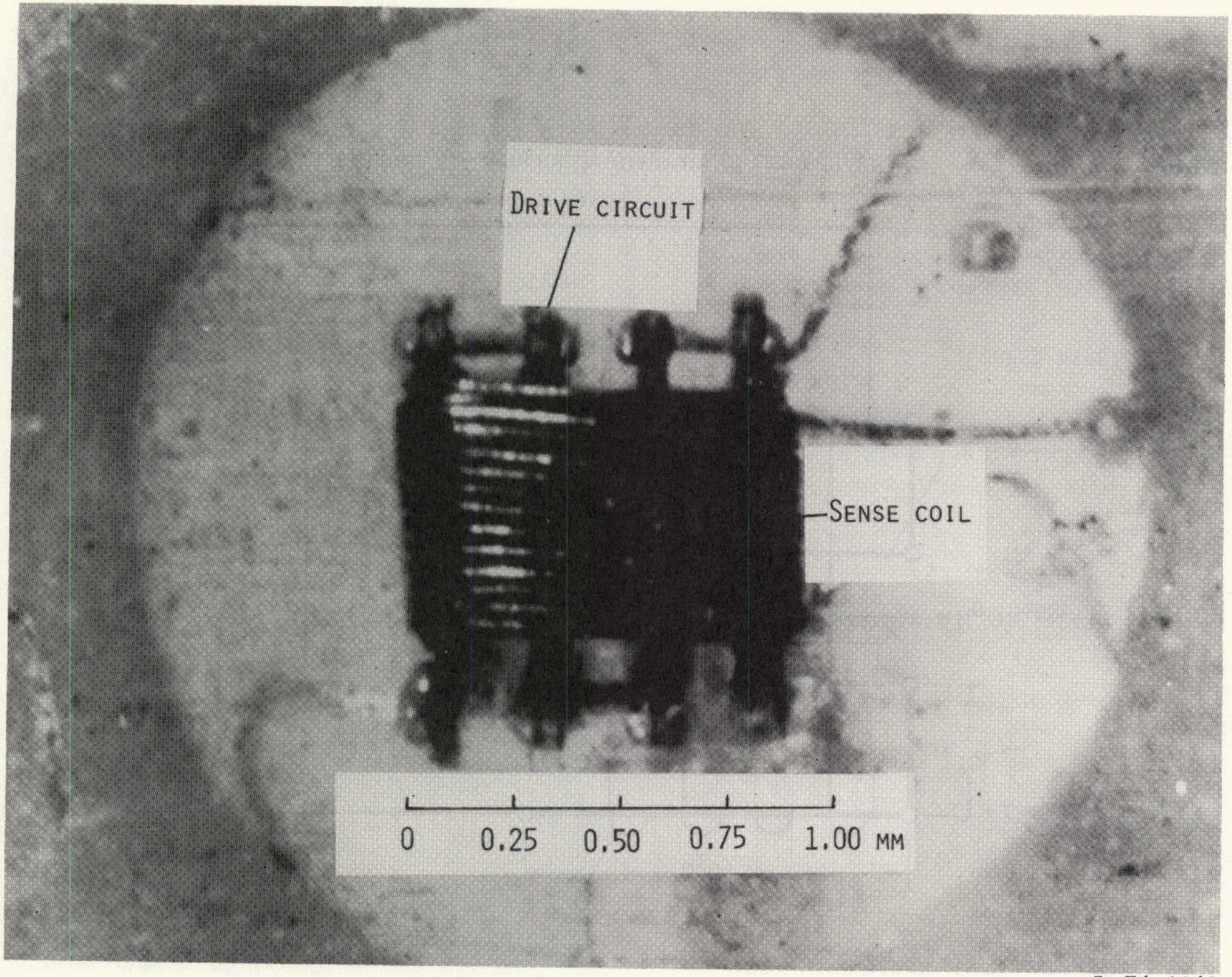

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Figure 2.- Photograph of completed transducer.

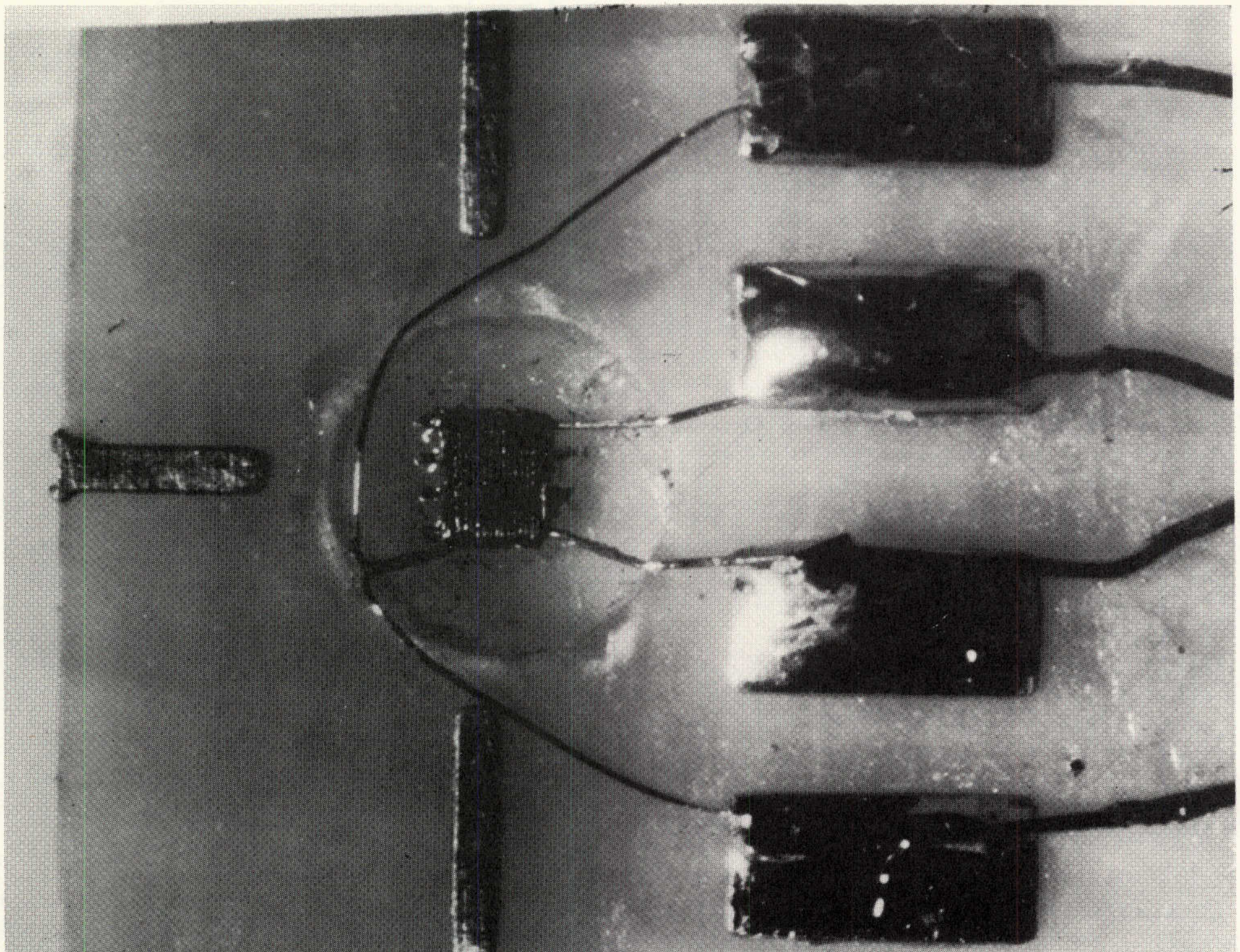

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Figure 3.- Photograph of mounted transducer.

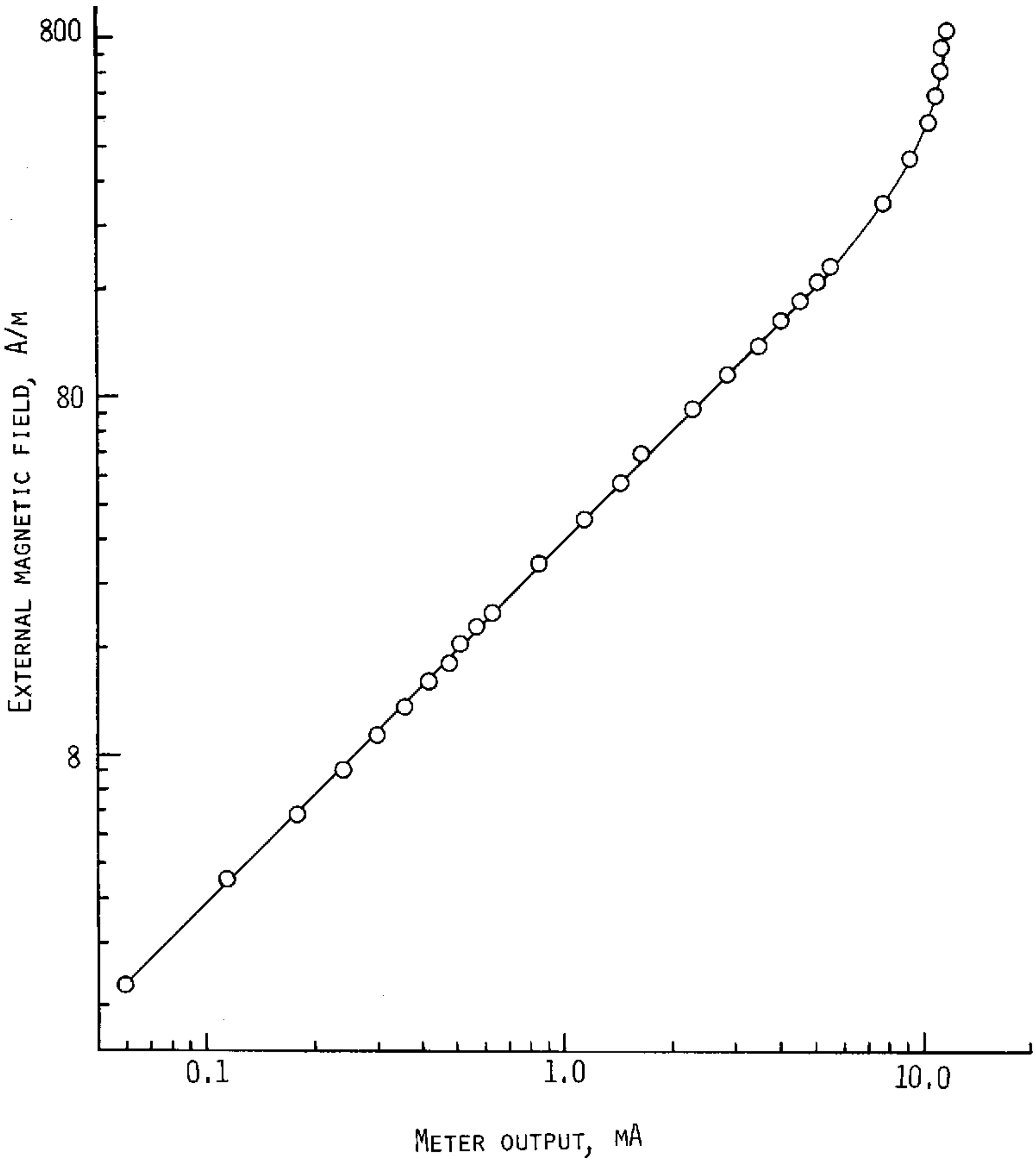

Figure 4.- Calibration curve for magnetometer.

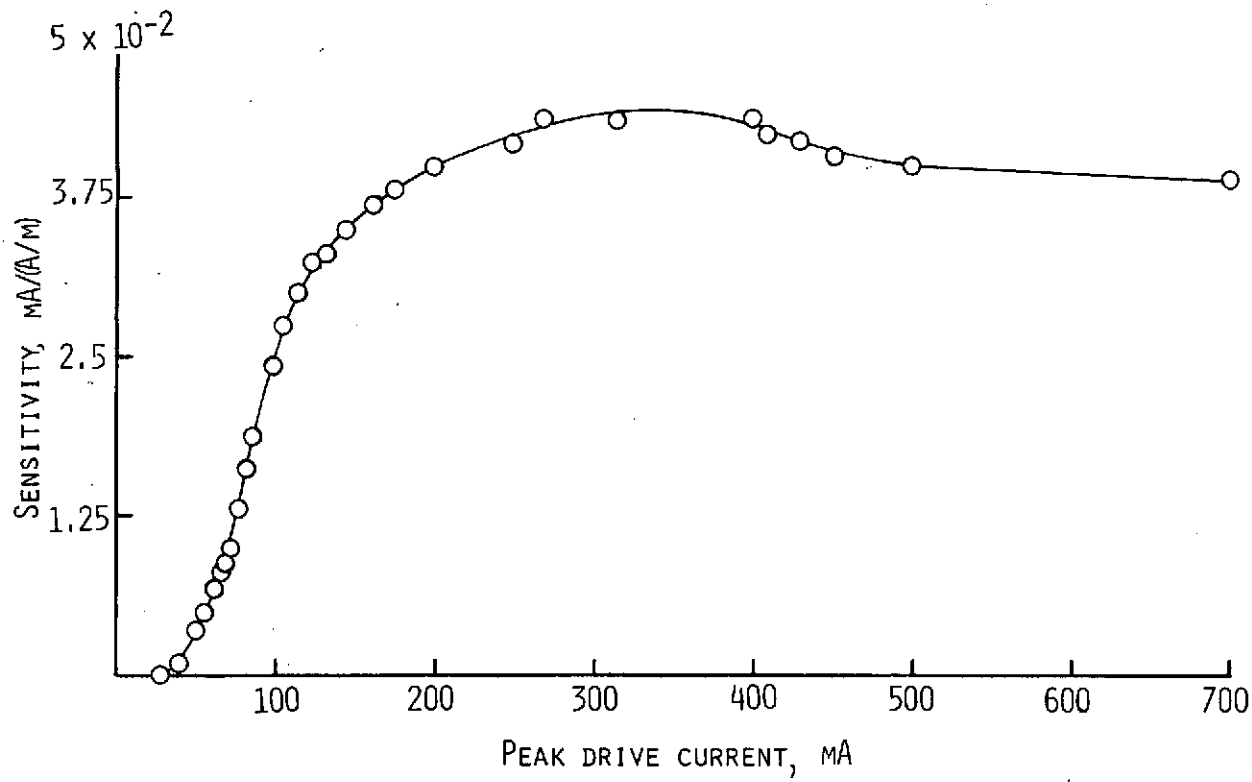

Figure 5.- Magnetometer sensitivity dependence on drive current.

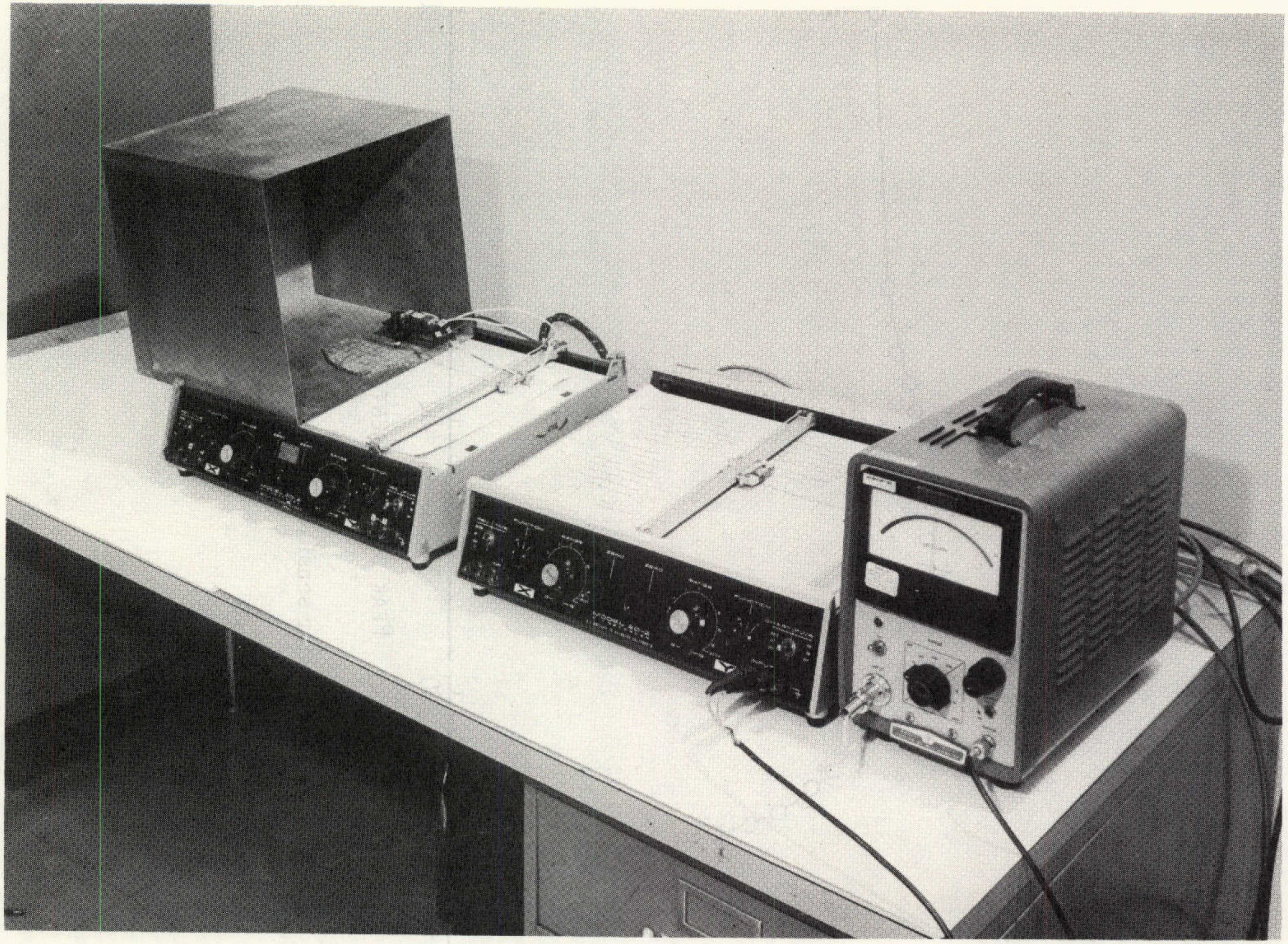

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Figure 6.- Photograph of magnetometer and scanning apparatus.

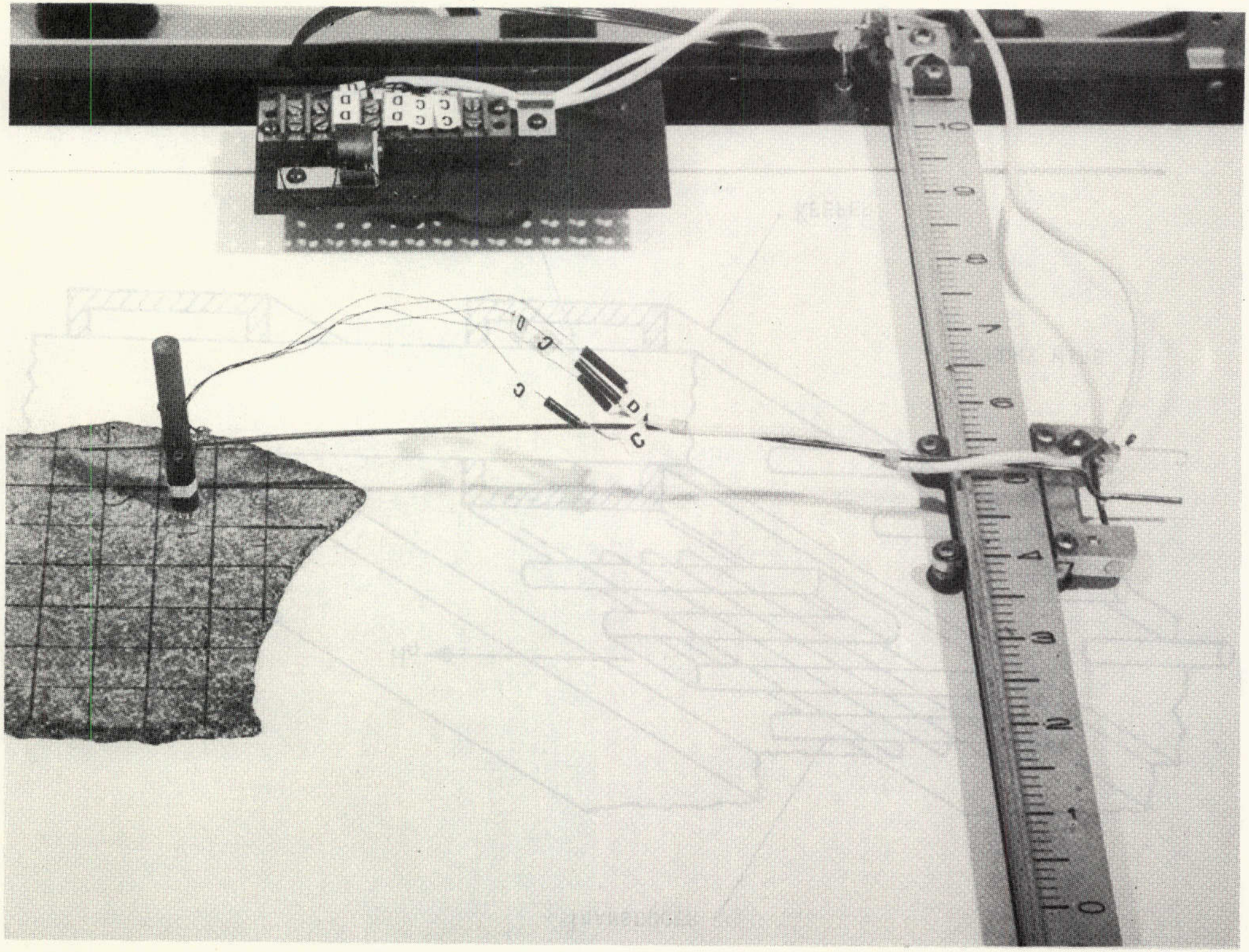

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Figure 7.- Photograph of transducer holding mechanism.

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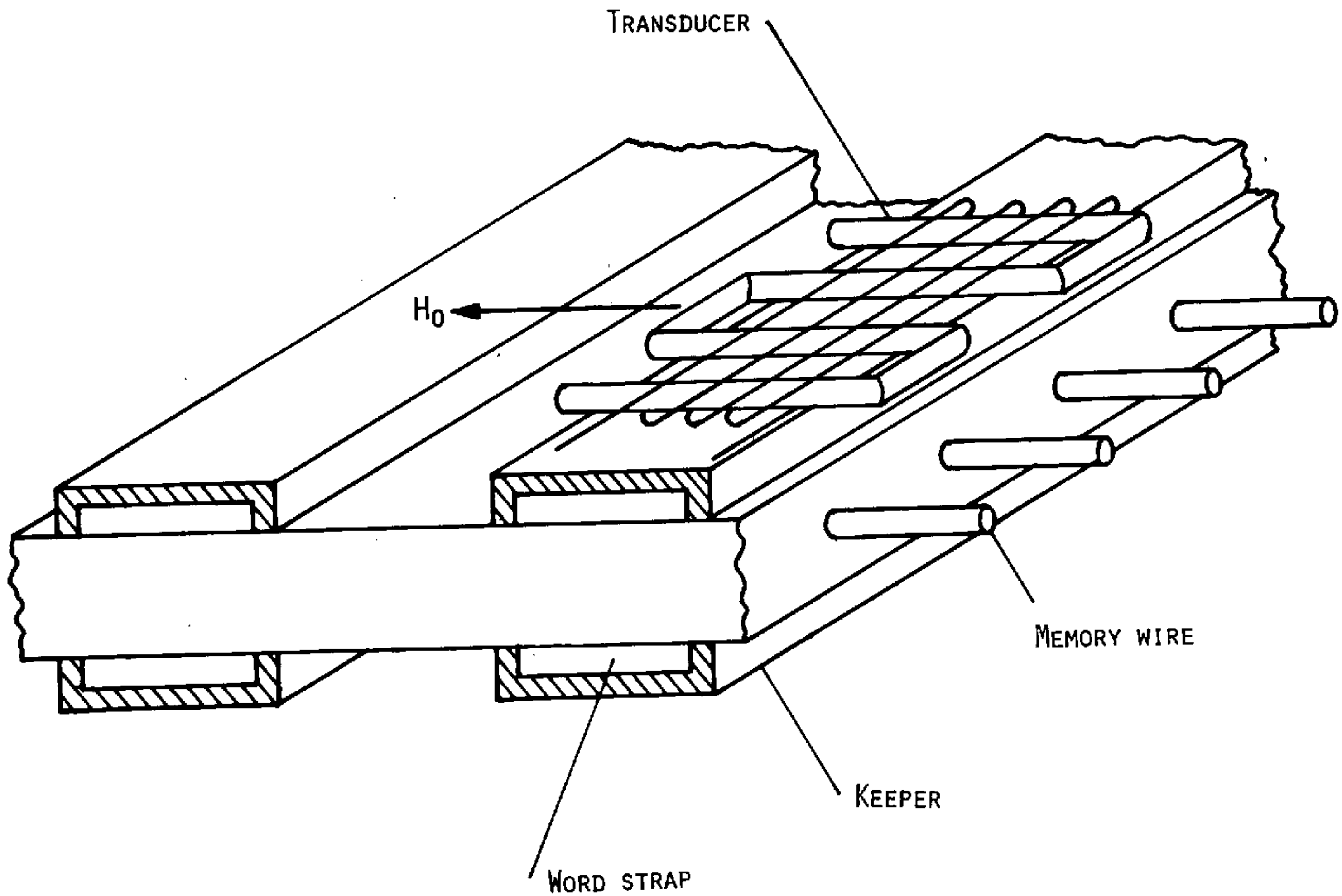

Figure 8.- Cross section of plated-wire memory.

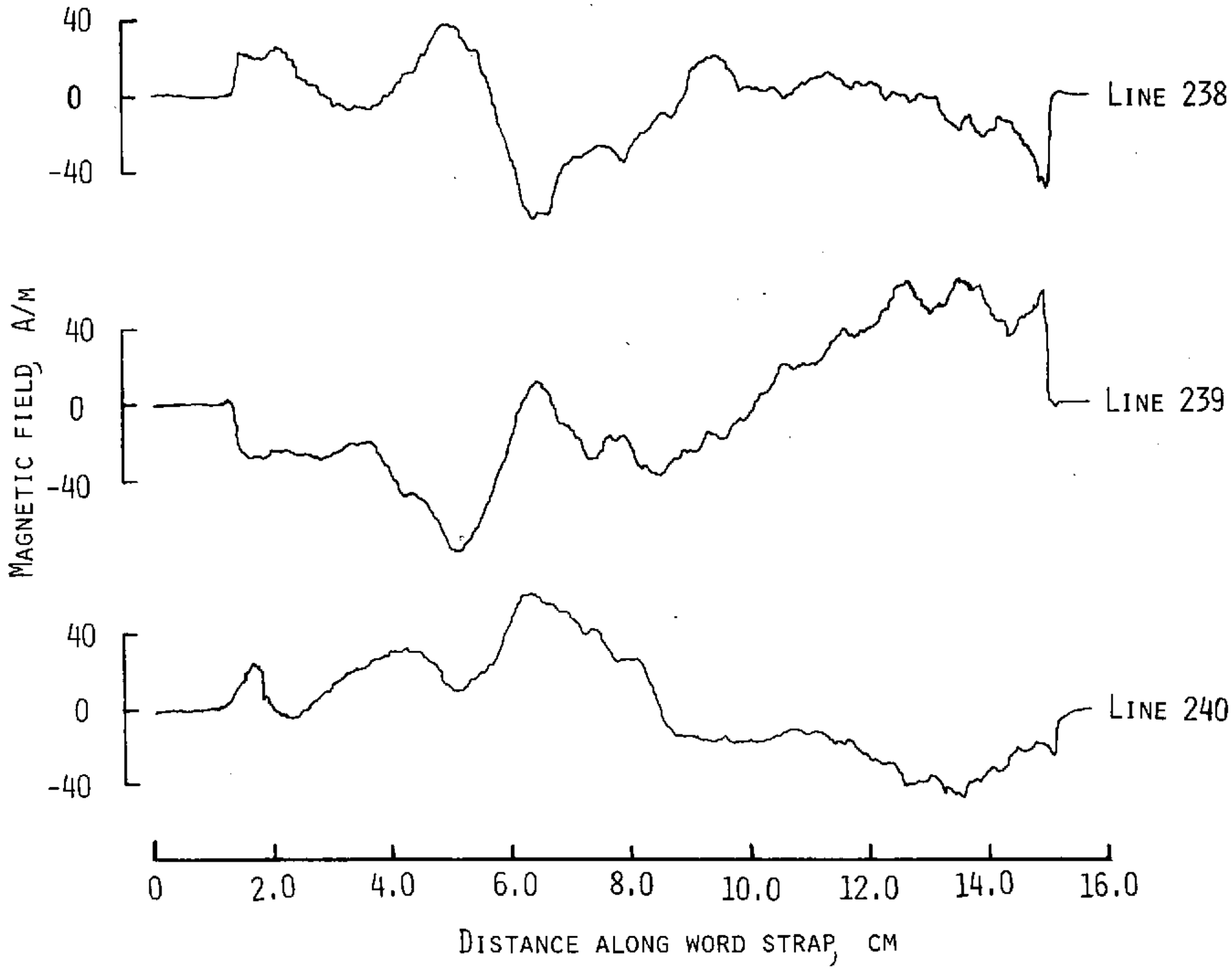

Figure 9.- Magnetic field as a function of distance along word strap.

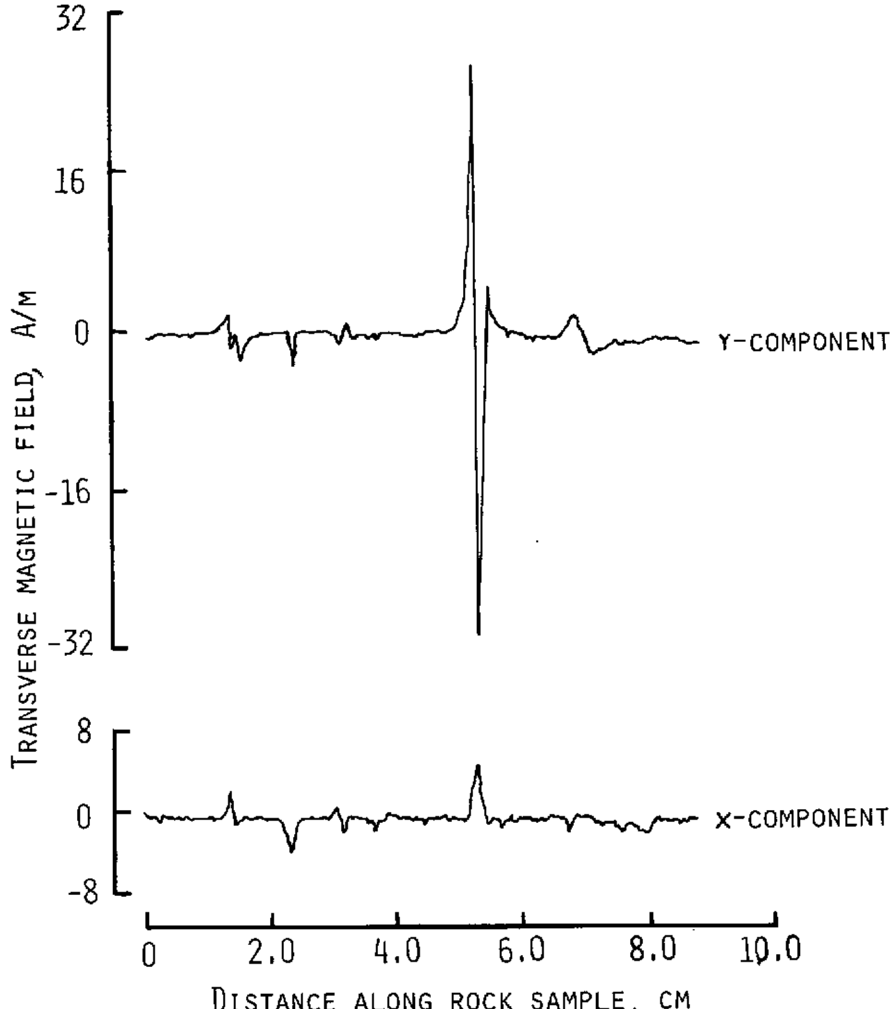

Figure 10.- Magnetic field as a function of distance across rock sample surface.

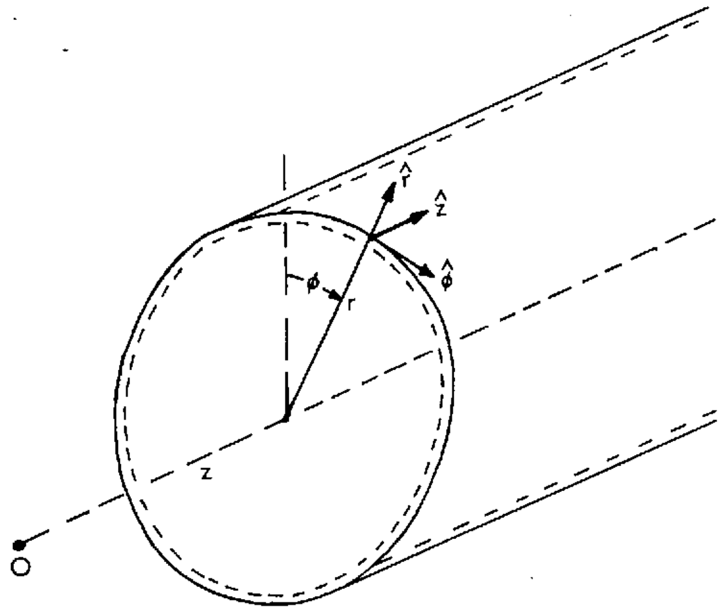

Figure 11.- Plated wire coordinate system.

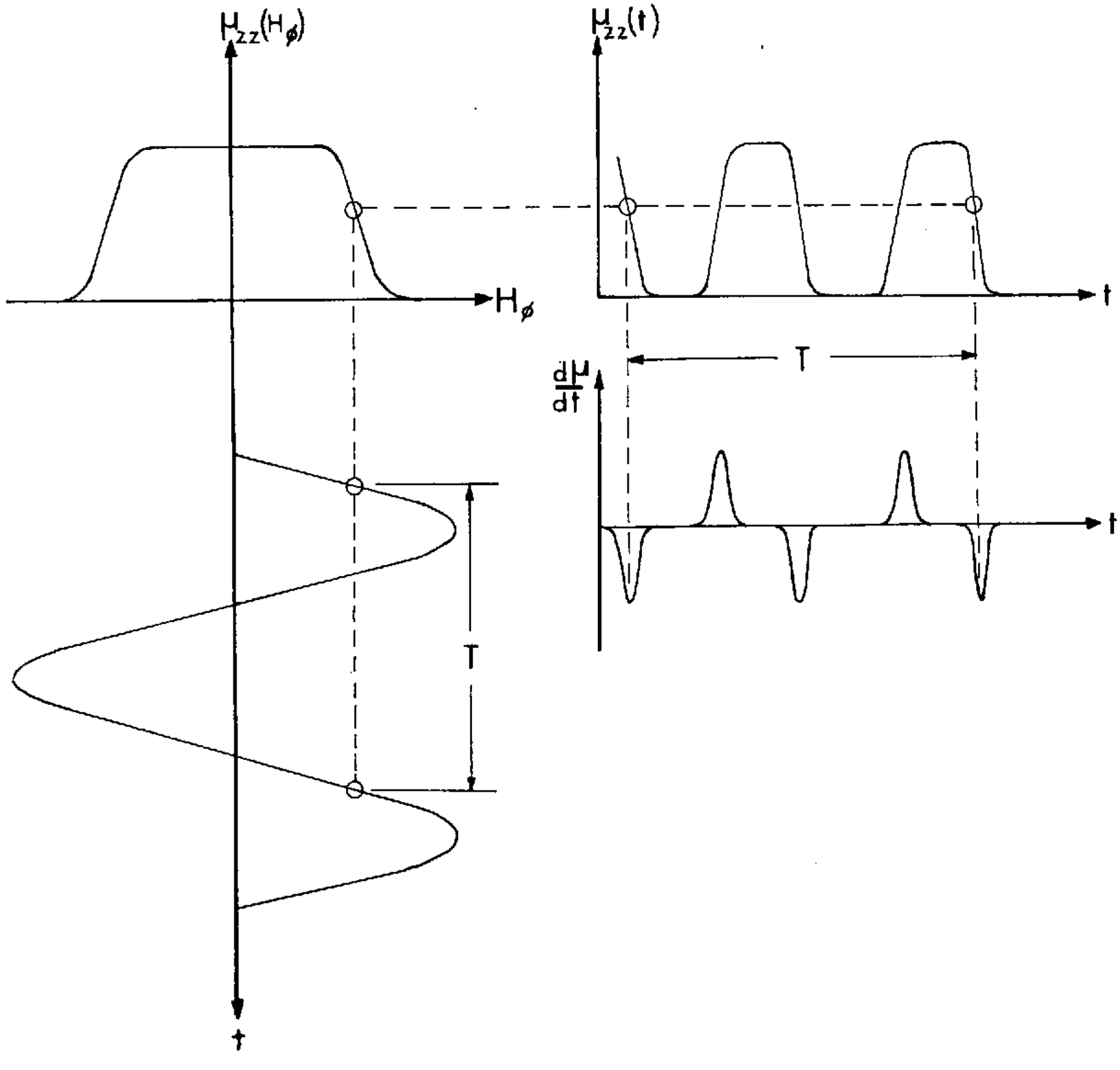

Figure 12.- Idealized waveform description of transducer operation.